

Chapter 2

Specificity of Structure and Properties of Timber Species

Abstract This chapter describes the data related to micro- and macro-structure of deciduous and coniferous species, dry and wet density, and basic relationship between thermal conductivity, specific heat capacity, thermal diffusivity, thermal inertia and humidity, and density and anisotropy of various types of timber, and some genetic aspects of timber diversity are considered. The basic relationship between mechanical properties and ambient temperature is presented.

2.1 Macro- and Microstructure of Deciduous and Coniferous Timber Species

In a visual inspection of the anatomy of coniferous and deciduous timber trunks in cross section, the macrostructural features they have in common are easily seen. In the first place, these are more or less well-defined spatial zones (layers).

The outer zone is the bark consisting of a cork layer of dead plant cells, which provide the tree with basic protection from external damage and a thin inner live bast layer. In many timber species, the light sapwood zone stands out from the darker central heartwood zone, where the latter formed as a result of gradual changes and dying-off of living cells in sapwood. Sapwood width depends on the time the heartwood formed. The later this phase starts, the wider it is. But in certain species (spruce, fir, beech, aspen), the borderline between sapwood and heartwood is poorly discerned visually, but the heartwood zone has lower moisture. The trunk pith is a dark-colored zone formed during initial trunk and branch elongation. Certain timber species have clearly visible 0.05–1 mm wide pith rays in cross section, which connect different layers from pith to bark and serve to store and transport nutrients.

Between bark and wood, there is a cambial layer of living cells, which can only be seen through a microscope. Wood and bark elongation and diameter growth occur through plant cell division and growth in this layer. Annual growth of wood is called the growth layer. Every growth layer consists of earlywood and latewood zones. The

earlywood zone located closer to the pith is usually less solid and outwardly clear. Earlywood is formed during the first period of vegetation and contains a certain number of living cells. Latewood is formed at the end of the vegetation period and is more solid and darker. The earlywood layer carries water and nutrients upward. Latewood mainly performs mechanical functions. Its content often serves as the basis for assessing the robustness of timber material (Ugolev 2001).

In certain tropical areas, the vegetation period may last whole year. In such cases, there is no clearly outlined borderline either between early and latewood layers or between growth layers.

For all natural zone characteristics uniformity, every species and variety of timber has its specificity. They show up particularly in the quantitative relationship between macrostructure elements, in their dimensions, colors, and properties (Ugolev 2001).

It should be noted that certain elements of timber structure are inherent only in deciduous species or only in particular varieties of coniferous species. Thus, resin channels are a feature only of coniferous species. In cross sections of pine, cedar, larch, and spruce, they can be seen as 0.08–0.14 mm white spots. These spots are the cuts of vertical resin channels that thread the timber. Only deciduous species have pores (vessels) conspicuous in cross sections in the form of round holes.

Deciduous species are subdivided by pore location into species with diffuse-porous structure, where the pores are uniformly distributed in the growth layer, and species with ring-porous structure. In the latter case, large pores 0.2–0.4 mm in diameter are usually concentrated in the early zone of the growth layer forming a continuous ring, whereas small pores (diameter 0.016–0.1 mm) are concentrated in the late zone. Species with the ring-porous structure are differentiated by distribution of small pore groups in the latewood into radial, tangential, and disordered arrangement of these groups. In timber structures with the radial group arrangement (oak, chestnut), they have the shape of a tongue of flame. In the tangential arrangement, they form solid or dashed wavy lines (elm species) drawn along the growth layers. In the disordered arrangement (ash), small pores are seen in cross section as clear bars or dots (Fig. 2.1) (Ugolev 2001).

More in-depth information on the composition and microstructure of coniferous and deciduous timber species is obtained through modern chemical, physicochemical, and physical methods of analysis, including various electronic microscopy techniques that are able to identify structural elements with dimensions down to 0.1–2 nm.

The basic elements of wood structure are plant cells, which form tissues of various structures and functions. Every living cell of woody plants consists of metabolically active protoplast encased in a membrane. A membrane is a cell wall consisting of a fairly robust multilayer formation. The cell wall is a specific attribute that distinguishes a plant cell from an animal cell.

Plant cells are subdivided by shape into two groups: multifaceted or round parenchymal cells 0.01–0.1 mm in diameter and prosenchymatous cells with an oblong shape. The diameter of prosenchymatous cells ranges between 0.01 and 0.05 mm, and their length from 0.5 to 3–8 mm. Their walls are usually thicker than parenchymal cell walls. In the wood of a growing tree, only 5–10 % of early zone

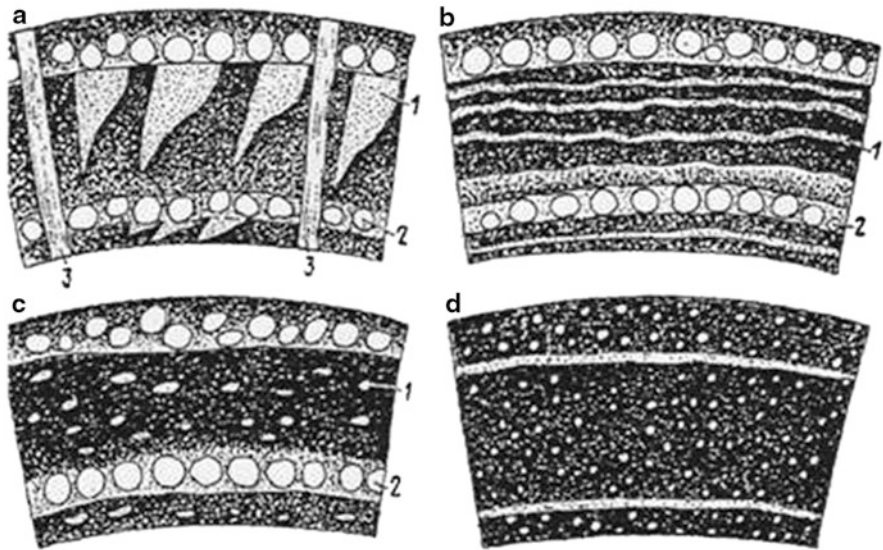


Fig. 2.1 Pore arrangement in deciduous timber species: (a–c) ring-porous structure species with radial, tangential, and disordered arrangement of small pores in the late zone; (d) diffuse-porous structure: 1 small pores in the late zone, 2 large pores in the early zone, 3 wide pith rays

parenchymal cells maintain metabolically active protoplast. The other cells die off after the maturation process is completed and are filled with water or air instead of protoplast.

Therefore, the timber framework is made of cell membranes that mainly perform mechanical functions. The basic substance is cellulose, which renders the cell membrane stable and robust.

Cell wall structure, formation and development are addressed in a large number of scientific works. We are particularly interested not only in studies of the physical microstructure of timber but also of the chemical composition and structure of its individual elements during woody plant growth and their common and distinguishing features for various species (Ugolev 2001; Antonova 1999).

The cell wall is formed in the process of living cambium cell division. Division starts with the formation of a cell plate that splits the protoplast of the primary plant cell into two parts and later turns into middle lamella between daughter cells. It has a high pectin content. The daughter cells initially acquire primary membranes formed from cellulose macromolecules. Cellulose macromolecules in the primary membranes have a relatively low degree of polymerization (they contain from 2,000 to 4,000 repetitive glycosidic linkages in the main chain) and are polydisperse. Due to hydrogen bonds between molecules, they group into microfibrils. In primary membranes, cellulose microfibrils are arranged haphazardly about one another. Between them lie the substances of the so-called matrix (pectins and hemicelluloses) as well as water molecules. Matrix plasticity facilitates the expansion of daughter cells and an increase in their longitudinal and lateral dimensions. When cell growth

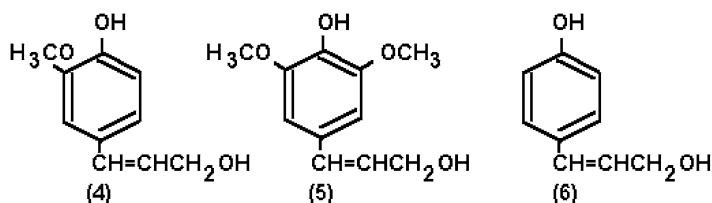
by expansion is completed, the secondary membrane is formed. Cellulose in the secondary membranes has a higher average degree of polymerization (up to 10^4) and is practically monodisperse. A secondary membrane, which is often called a secondary cell wall, consists of three layers, where cellulose microfibrils are arranged in each of them in the form of spirals at different angles to the cell's longitudinal axis. In the outer layer S_1 of a secondary membrane, the microfibril spirals are oriented at an angle of 60° – 80° in coniferous species and at about 45° in deciduous species. The S_1 layer is 0.2 – $0.5\ \mu\text{m}$ wide in earlywood cells but may be up to $1.0\ \mu\text{m}$ in latewood. The dominating layer of the cell wall secondary membrane is the middle layer S_2 . Cellulose microfibrils in this layer are inclined at 5° – 15° in earlywood cells and up to 30° in latewood. This S_2 layer is 1 – 2 and 3 – $8\ \mu\text{m}$ thick in plant cells of earlywood and latewood, respectively, depending on timber species and variety. The inner layer S_3 of the cell wall secondary membrane is 0.1 – $0.2\ \mu\text{m}$ thick, regardless of early or late plant vegetation period, and has gently sloping cellulose microfibrils with a spiral inclination angle of 90° .

As the active growth of cells comes to an end, the nature of polysaccharides of cell wall matrix changes. A predominant content of pectins turns into a predominant content of hemicelluloses. In addition, the set of different types of hemicelluloses also changes. One more cell wall layer adjacent to the S_3 layer and covering the cell's interior occurs in the structure of cell walls of certain timber species. This is the so-called warty layer W. It consists of a membrane and lumpy formations, i.e., warts, has an amorphous structure, and contains hemicelluloses, a small amount of lignin and simple proteins.

Lignin serves as an additional substance strengthening cell walls. Study of the lignification process of cell walls in coniferous and deciduous timber species at individual phases of their vegetative growth is of great interest from various points of view, including the structure of lignin itself (Antonova 2000). The example of larch shows that the onset of lignification corresponds to the start of secondary membrane formation in cell walls. Lignin is formed, first of all, around the corners of middle lamella in the intercellular space of adjacent plant cells. During the formation of earlywood, this phase corresponds to deposition of 22 – $26\ \%$ of the wall mass in the secondary membranes. In latewood formation, only 6 – $10\ \%$ of the wall mass, mainly represented by cellulose, is deposited prior to the onset of lignification. At the time lignification of plant cell walls starts, the product of lignin biosynthesis is most likely its precursor substance, because although it contains the building blocks of lignin molecules, it has low molecular mass (Antonova 2000). The progress of the cell wall lignification process is not the same in earlywood and latewood. In earlywood formation, lignification proceeds gradually and achieves its maximum intensity at the last phase of plant tissue maturation. In latewood formation, the maximum intensity of lignification is seen right from the start and decreases toward the end of the vegetation period. Lignin distribution in the cell wall is uneven. The layers that were deposited first usually contain more lignin. For this reason, lignin content around the corners of middle lamellas, in the middle lamellas themselves, and in primary membranes of plant cells is higher toward the end of the vegetation period compared to secondary membranes.

It must be emphasized that lamellar morphology of cell walls is a common feature of all principal structural elements of plant tissues in various timber species (tracheids, libriform fibers, pores, pith rays). There is a difference in the details of structural organization at the quantitative level and in the specific character of biosynthetic processes in the chemical components of structural elements (Goodwin and Mercer 1986). A good illustration of this is the difference in formation and composition of lignin in the plant cells of coniferous and deciduous timber species (Antonova 2000; Antonova et al. 2002).

Lignin of coniferous timber species has a predominantly guaiacyl type of three-dimensional polymer buildup with phenylpropanoid repeating units, which contain one phenolic hydroxy group and one methoxy group in an aromatic ring. The source of these units is coniferyl alcohol. Syringyl type (most conspicuous in the lignin of earlywood) and *n*-coumaric phenylpropane units have also been discovered. Their sources are sinapic and *n*-coumaric alcohols, respectively. Phenol-containing aromatic structures (coniferyl alcohol – 4, sinapic alcohol – 5, *n*-coumaric alcohol – 6) are shown below.

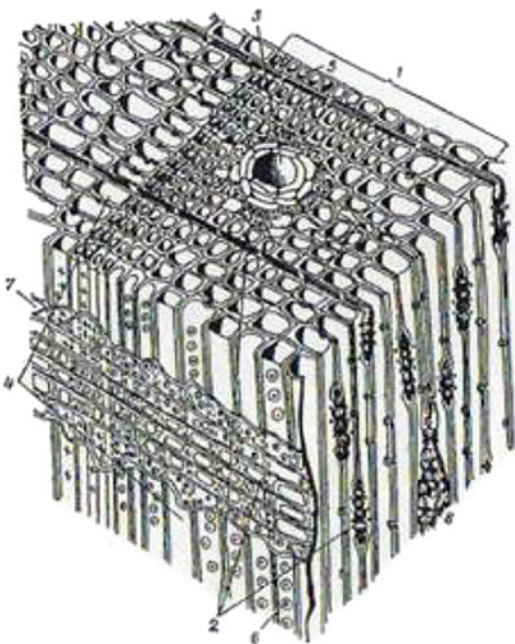


Lignin macromolecules of deciduous timber species include both guaiacyl and syringyl repeating units with two methoxy groups in a phenolic ring. That is why lignin of deciduous species is often considered a copolymer of coniferyl and sinapic alcohols in various ratios between them depending on timber variety. The author of work (Antonova et al. 2002) states that lignin with guaiacyl repeating units is mainly located in middle lamellas, which surround all basic structural elements of oak wood. Syringyl lignin is concentrated in the walls of libriform and tracheid fibers, mainly latewood.

The microstructure of coniferous timber species consists of a system of fibers (tracheids) arranged along and across the trunk, pith rays, and vertical and horizontal resin channels located in the intercellular space (Ugolev 2001). Figure 2.2 shows the arrangement of microstructure elements of pinewood (typical coniferous species) in cross-sectional, radial, and tangential views of a trunk cut (Ugolev 2001).

On the radial walls of longitudinal tracheids of the earlywood zone in the growth layer, there are many large bordered pores (from 50 to 300 per tracheid). The walls of late tracheids have fewer pores. They are smaller, often have the form of slits, and may be found not only on radial but also on tangential walls. The pores of adjacent vertical tracheids located opposite each other transport nutrients and water in the horizontal direction. In the vegetation period, the flow

Fig. 2.2 Microstructure of pinewood in cross-sectional, tangential, and radial views



of liquid matter also goes in the same direction through pith rays, which in the dormant period function as storehouses of reserve nutrients. Separate elements in the microstructure of pinewood have the following volumes in approximate percentage:

Longitudinal tracheids	93 %
Pith rays and ray tracheids	6 %
Resin channels	1 %

According to certain other data, the proportion of ray elements in wood microstructure of various coniferous species ranges from 3.4 to 11.7 %, with 7 % as the average (Siau 1984).

The microstructure of deciduous timber species is more varied and complex compared to coniferous species. Figures 2.3 and 2.4 show the microstructure of deciduous timber with ring-porous and diffuse-porous structure, respectively.

In the typical ring-porous structure of oak (Fig. 2.3), a significant volume (up to 25 %) is occupied by large porous elements in the earlywood zone (200–400 μm in diameter) and smaller pores of latewood (30–40 μm in diameter). The pores are long vertical tubes built of short plant cells (segments) with wide cavities and thin walls. Pore cavities, as well as simple and scalariform (slit-shaped) perforations and bordered pores in the walls of pore cells, participate in the general aquiferous system of deciduous timber species. As a rule, a small number of porous tracheids are located next to pores, and they are a transitional form between typical tracheids and pores. In their structural organization, they resemble the segments of small pores.

Fig. 2.3 Ring-porous microstructure of oak wood

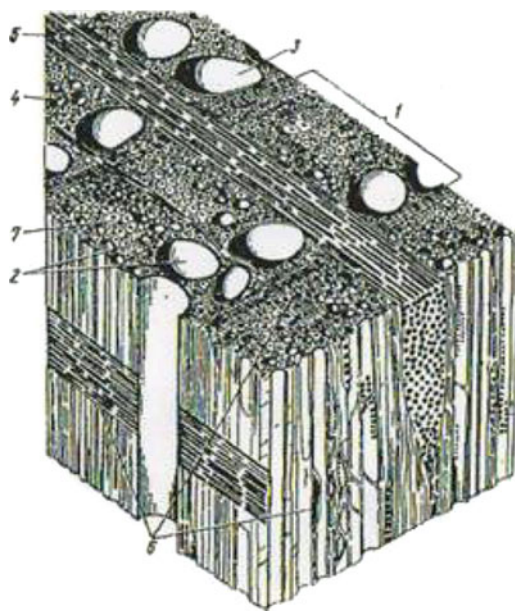
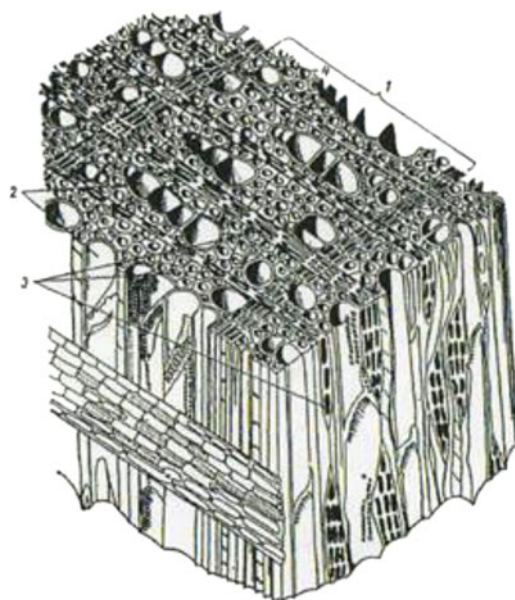


Fig. 2.4 Diffuse-porous microstructure of birch wood



The main mechanical function in deciduous timber species is performed by fibers, which fill from 20 to 75 % of the volume of wood pulp depending on the timber variety. These fibers consist of fiber tracheids and libriform fibers, which derive their names from the Latin words “libri” meaning bast and “forma” meaning

form. Libriform fibers are relatively short, very thin, and have narrow cavities and thick walls with slit-shaped pores. Fiber tracheids in deciduous species are shorter and narrower than tracheids of coniferous timber species and have thick walls with bordered pores.

Parenchymal cells of mainly horizontally arranged pith rays occupy a very significant volume (up to 40 %) in the microstructure of deciduous timber species. Parenchymal cells may be located within the ray width in one or several rows depending on the timber variety. Pith rays also show great diversity in height and may contain from several (in willow wood) to more than a hundred cell rows (e.g., beech wood) (Ugolev 2001). Vertical parenchymal cells (the so-called wood parenchyma) occupy less volume, partially performing the function of storehouses for reserve nutrients.

Timber with diffuse-porous structure (Fig. 2.4) differs from that with ring-porous structure in a higher volume content of pores (ranging from 20 to 60 %), their relatively even distribution in the growth layer, and uniform dimensions.

Pore diameter in the wood structure of most diffuse-porous timber growing in temperate climates ranges from 20 to 100 μm .

Volume distribution of structural elements characteristic of typical diffuse-porous timber may be represented as follows (Siau 1984):

Pores	55 %
Libriform fibers and tracheids	26 %
Wood parenchyma	1 %
Pith rays	18 %

Variations in the composition and ratio of structural elements in the timber of different species and varieties affect various timber properties, particularly important properties affecting wood combustion regularities such as density, moisture, heat transfer, thermochemical, diffusion, and some other properties.

According to contemporary notions about wood structure, the specific features of the conducting and transport systems play an enormous role in realization of individual genetic program of woody plant development (Siau 1984; Gamaley Yu 2004).

Without going into all the details of the complicated organization of the transport system in woody plants, let us mention its principal features. Today, the persistent idea is that there are two independent transport channels carrying counter flows: an upward flow of aqueous solutions of nutrients from the roots to needles or leaves of the crown and a downward flow of photoassimilates and metabolites from leaves (needles) to the roots. Thus, there are two poles for generating these flows or two opposite centers for controlling plant development and two zones for loading and unloading transportation lanes (Gamaley Yu 2004). Transportation lanes serve to distribute assimilates and metabolites among the cells and tissues of a plant. Cells of the living layer of cambium are involved in the formation of these transport lanes. After their division, the cells and tissues of the bast (called “phloem” in the

scientific literature) are deposited on one side, while wood cells (its conducting tissues have the common name “xylem”) are deposited on the other side. The upward flow of nutrients and water goes through xylem. The structural elements of wood performing conducting functions have already been addressed. The downward flow of assimilates and secondary metabolites derived from them occurs through the sieve cells and sieve tubes of the phloem (bast tissue). The structural organization of phloem is still poorly understood (Gamaley Yu 2004).

The transport system of woody plants, along with the on-range echelon of movement of various substances toward the trunk, includes a midrange echelon, i.e., radial intercellular flows in parenchymal tissues, as well as short-range transport inside the cells. The intercellular exchange process is the initial phase of all transport processes. One of the leading intercellular mechanisms is believed to be molecular transmembrane transfer of substances with the participation of carrier proteins as receptors and transporters. Special genes in a plant genome are responsible for carrier protein biosynthesis (Gamaley Yu 2004). The transport system of woody plants generally performs a regulatory function in the delivery and distribution of various assimilates and their derivatives among the cells and tissues, thus influencing all processes of plant development.

2.2 Biological and Genetic Aspects of Timber Species Diversity

The first, most ancient forests came into being in the Paleozoic era of the Earth’s evolution more than 300 million years ago and consisted of a cluster of evergreen coniferous (gymnospermous) plants. Deciduous (angiospermous) woody plants appeared later, in the Jurassic period of the Mesozoic era 165 million years ago. They are believed to originate from Mesozoic gymnospermous plants, were at first evergreen, and only later turned into plants with seasonal leaf appearance and shedding. They became widespread in the Cenozoic era 75 million years ago, and they continue to spread to the present day. Further evolution of the ancient plant forms follows the sequence from big trees to arboreal forms of shrubs, then to perennial grasses, and finally to annual grasses. Flowering angiospermous plants further evolved into dicotyledonous and monocotyledonous plants. The best-known contemporary monocotyledonous plants are palms. However, palms are not considered genuine trees, because they originate from ancient herbaceous plants (Zhdanov 1990). According to the theory of evolution, the division of the plant kingdom into arboreal forms and grasses must be traced back to the Cretaceous period of the Mesozoic era (135–110 million years ago) (Zhdanov 1990).

Contemporary deciduous timber species differ from coniferous species by a greater number of varieties. For example, in the European part of Russia alone, there are 70 varieties of birch and 50 varieties of the poplar genus *Populus*, while 150 varieties of eucalyptus grow on the Black Sea Coast of the Caucasus (Ugolev 2001).

Understanding of the evolution and polymorphism of arboreal populations is based on the understanding of the inherited, genetic principles of their diversity and adaptation to the environment. One of the fundamentals of genetics is the chromosome theory of heredity, according to which all hereditary information on an organism's development and properties is accumulated mainly in molecular chromosome structures. They are contained in the nuclei of all the organism's cells. The material carrier of information is the genome – polymer deoxyribonucleic acid (DNA) is the physical information medium.

In order to envision the mechanism of hereditary transfer of features from parent organism to daughter organism, let us start by briefly analyzing the intercellular organization of a protoplast – the metabolically active component of a plant cell.

A protoplast consists of two parts: cytoplasm and vacuole. They are separated from the cell wall and from each other by membranes (so-called plasmalemma and tonoplast, respectively). Cytoplasm is a liquid material with varying density. It contains multiple corpuscular inclusions, each of which is surrounded by its own membrane with specific porosity and permeability.

The largest inclusion is the nucleus. Its nucleoplasm is where nuclear chromosomes are contained. It also contains a karyonucleus, where nuclear ribosomes originate. Ribosomes, which contain macromolecules of ribonucleic acids (RNA), are the most numerous corpuscular inclusions in cytoplasm. They may be both in the unbound state and bound state with the membranes of other inclusions and may be part of intracellular organelles such as chloroplasts and mitochondria. The group of small corpuscular inclusions consists of spherosomes, peroxisomes, and glyoxisomes with various functions. Some of them are present in photosynthetic cells of leaves, and others in the cells of seeds. The major membrane inclusion in the protoplasm is endoplasmic reticulum, which consists of interlocking membrane tubules and bubbles. The membrane of endoplasmic reticulum is connected to the nuclear membrane. Dictyosomes (which have the appearance of stacked flat bubbles) of the Golgi apparatus, which combines a corpuscular and membrane structure, are also closely linked with these same membranes. Intracellular transport exchange takes place due to this network of links. It is assumed that the synthesis of many compounds, including polysaccharides of the wall cell matrix, occurs in the dictyosomes of the Golgi apparatus (Goodwin and Mercer 1986). Part of these substances goes into a vacuole through the tonoplast. Vacuoles serve as a sort of storage for the nutrients that a plant accumulates. Although chloroplasts and mitochondria possess a certain genetic autonomy because they contain their own DNA and ribosomes, the decisive role in transferring hereditary features belongs to the nucleus.

Mitochondria are the centers of intracellular respiration owing to the oxidation of substances into CO_2 and H_2O with energy emission and oxidative phosphorylation with the formation of adenosine triphosphate (ATP), an essential compound for biosynthesis, and they also contain the ferments for many important metabolic reactions (Goodwin and Mercer 1986). Depending on the type and dimensions of a cell, one plant cell may have 100 or even 1,000 mitochondria.

Chloroplasts are detected in the cells of leaves and all green tissues of woody plants. They are not present in the living cells of sprouts and roots. One cell usually holds from 2 to 400 of these corpuscular inclusions. The processes that occur in chloroplasts are formation of chlorophyll, biosynthesis of carotenoids and fatty acids, and photosynthesis of monosaccharides – precursors of oligosaccharides, the most important of which is saccharose.

Genomes of mitochondria and chloroplasts are not only smaller than nuclear DNA but also differ in nucleotide composition. Furthermore, mitochondria and chloroplasts have many copies of DNA molecules in contrast to DNA of nuclear chromosomes. Ribosomes located in chloroplasts and mitochondria also have smaller dimensions than ribosomes in cytoplasm.

As previously stated, DNA functions as the carrier and depositary of hereditary information. This information is coded in the genes, which are specific linear sections (blocks) of DNA macromolecules.

Each chromosome is a sort of nucleoprotein DNA complex with a large number of histone proteins of relatively low molecular weight. Two gigantic chains of DNA molecules, whose length in expanded form may amount to 1–2 m, form a double spiral. After further curling, this spiral provides a still better level of compact packing of DNA, so that DNA may occupy only 40–50 μm^3 within the nucleus volume. Therefore, a plant cell may hold not one but many chromosomes. Access to DNA information coded in the genes is only possible after dismantling all levels of packing and disengagement of the double DNA spiral. A major role in this DNA gene deactivation procedure is played by histones, the proteins mentioned above.

Information contained in the DNA molecule is not actualized immediately but is first decoded onto a matrix, messenger macromolecule of ribonucleic acid (mRNA) and then transported by transfer RNA molecules (tRNA) into the cell cytoplasm for protein biosynthesis. Protein synthesis is carried out with the participation of cytoplasm ribosomes and ferments. Cytoplasm ribosomes based on information transferred from the genes by mRNA molecules with the aid of tRNA combine various amino acids in sequential order and synthesize the protein of the coded composition.

From the chemical point of view, DNA is a sequence of deoxyribonucleotide structural units interconnected by phosphodiester linkages through 3' → 5' carbon bonds of the ribose carbohydrate cycle. Deoxyribonucleotide units contain purine bases, adenine and guanine, as well as pyrimidine bases, thymine and cytosine. The DNA structural link is shown in simplified form in Fig. 2.5.

A DNA macromolecule may contain various combinations and sequences of nucleotides with the bases indicated above. Every three sequences of nucleotides capable of coding the synthesis of one amino acid in a protein molecule are called a codogene, whereas each such triplet in the corresponding macromolecule of messenger RNA is called a codon and anticodon – in transfer RNA.

RNA macromolecules are similar in chemical composition to DNA, because they consist of a row of ribonucleotides linked by phosphodiester linkages in 3' → 5' position of the ribose cycle. But in contrast to DNA, one of the nucleotides of RNA structural units contains a uridine base instead of thymine.

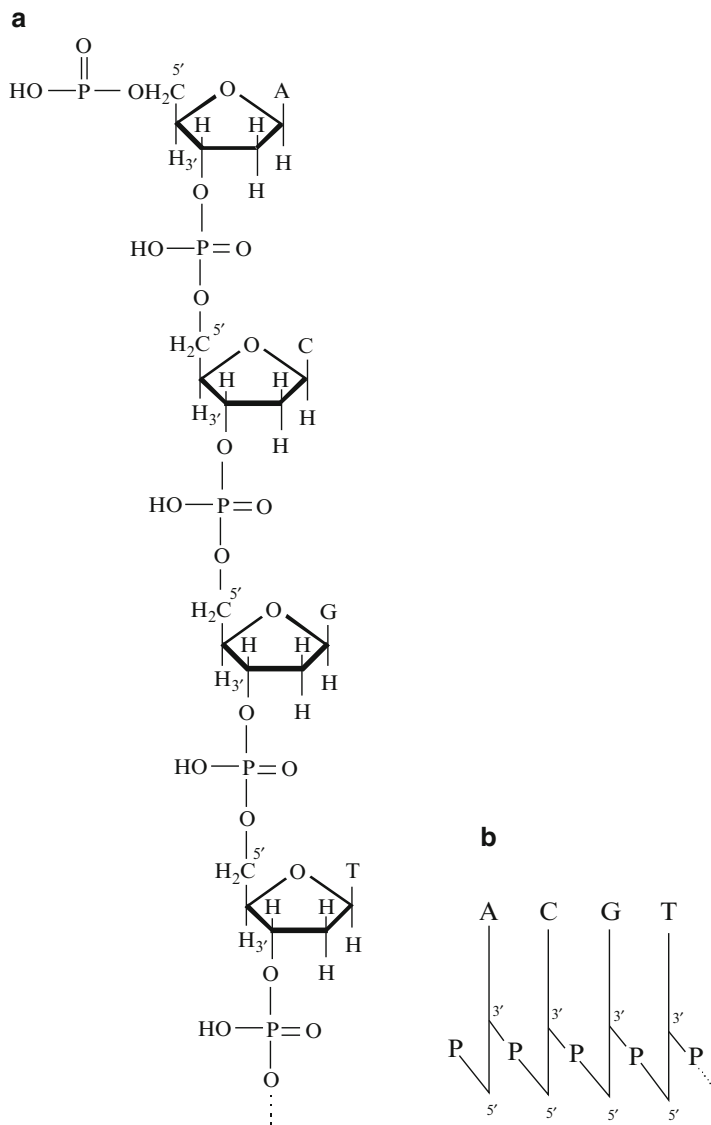


Fig. 2.5 Primary structure of the polydeoxyribonucleotide chain (**a**) and its contracted representation (**b**). A adenine, C cytosine, G guanine, T thymine

Intra- and interspecies polymorphism by chromosome number in plant cells was discovered in the first half of the twentieth century. Every plant species has an inherent set of a strictly determined number and type of chromosomes in the cell nuclei. This set is connected to the nature of the cell division process and to the evolution of plant cell structure.

The process of plant cell division occurs simultaneously with the cycle of doubling and division of chromosomes and other cell components. The newly formed cells maintain a strictly constant number and set of chromosomes intrinsic to the given species of woody plant.

According to the chromosome theory of heredity, the basis of biological diversity of woody plants is the difference in chromosome set types in the cells. The baseline is a single, so-called haploid set with one molecular DNA chain in the chromosome (haplotype is denoted by the letter “ n ,” where n is the chromosome number). A haploid chromosome set is found in germinal cells of an organism and in the nuclei of plant fragments. Thus, in deciduous species, the pistillate haploid generation is enclosed in the embryo sac located in the seed-bud, whereas staminate generation is located inside the pollen grain.

A double, or diploid set ($2n$), consists of 2 haploid sets. It is formed during fertilization as a result of the combination of maternal and paternal haploid sets. One more type is the polyploid set, where the cell nuclei contain more than two chromosome sets. Plants with multiple haploid chromosome sets are correspondingly triploid ($3n$), tetraploid ($4n$), and so on. Diploid chromosomes undergoing the cycle of duplication and division inside the cell nucleus without breaking its membrane may form tetraploid ($4n$) and then multiploid nuclei, e.g., hexaploid ($6n$) or octaploid ($8n$).

The chromosome composition of many widespread woody plants has now become known. Polymorphism of coniferous species has been studied more in this respect. Thus, the number of chromosomes in plant cells has been determined in about 80 % out of 800 studied coniferous species (Grif 2007). Coniferous plants most commonly have a diploid set with large chromosomes $2n = 16\text{--}24$. Exceptions are the natural hybrid – polyploid of Sierra redwood with $6n = 66$ chromosomes and golden larch with chromosome set $4n = 44$ (Grif 2007; Tsarev et al. 2000). A triploid hybrid of larch was artificially obtained, and it is distinguished by rapid tree growth and resistance to low temperatures (Tsarev et al. 2000).

Deciduous timber species show more diversity compared to coniferous species. Along with diploid type, widespread occurrence of intraspecific and interspecific polyploidy has also been observed in them (Grif 2007). The chromosome number in the nuclei of deciduous species cells may vary over a wide range (from 4 to 200). As a rule, as the chromosome number increases, their dimensions are reduced. Interestingly, polyploidy enhances the intensity of synthesis of various useful chemical compounds. The optimum polyploidy level in deciduous species is a triploid set of chromosomes. It may be the result of environmental stress or obtained through dedicated hybridization. For example, the triploid versions of poplar, birch, and alder, which feature not only rapid growth but also high-quality wood, were obtained by hybridization of diploid and tetraploid forms of woody plants. Polyploids are especially numerous among the willow and birch families. For example, within the *Salix* genus of willows, whole polyploid rows were discovered with chromosome numbers 38, 44, 57, 76, 88, 114, 152, and 190. They are represented by two polyploid series with main haplotypes $n = 19$ and $n = 22$. The specified row numbers include haploid chromosome set $2n = 38$ and a set of

higher forms up to decaploid with chromosome number $10n = 190$. Chromosome numbers 44 and 88 in this row are attributed to the diploid and tetraploid versions and in the second series of haploid set $n = 22$ (Afonin).

Certain woody plants typically have an aneuploid chromosome set in plant cells. Aneuploidy along with polyploidy is one more type of mutation resulting from dilation or addition of haploid chromosomes to the already existing set in the cell. Thus, along with the tetraploid version of the Siberian pea shrub with 32 chromosomes in its nuclei, aneuploid versions have been discovered with 27 and 29 chromosomes (Borodina 1982).

At present, it has become evident that polymorphism of woody plants is based on specificity of molecular structure and great variety of genome (DNA) states.

Possible molecular mechanisms that change the state of genomes, namely, of their active part, are addressed in work (Romanovsky 1994). These mechanisms may be changes in the conformational state of DNA sections and in the activity of genes linked to these sections; activation or repression of genes as a result of proteins bonding with certain DNA sections or disruption of these bonds; a change in gene order through rearrangement made by ring structures; reaggregation of genetic information through crossing over. The phenomenon of crossing over consists in modification of the qualitative composition chromosomes without altering their number. This happens as a result of interchange of certain sections between closely adjacent chromosomes, passage of part of the genes from paternal chromosomes to maternal chromosomes, and vice versa.

Regarding polymorphism as a consequence of various mutations in a plant organism resulted in subdivision of mutations into a series of classes or types (Grif 2007). The following types are the most common among timber populations:

1. Gene (point) mutations – when one or several pairs of nucleotides in DNA are substituted for others not involved in prominent chromosome alterations.
2. Chromosome mutations like crossing over and aneuploidy.
3. Genome mutations involving alterations in the number of chromosome sets. Polyploidy is the most common type of genome mutagenesis. It predominates due to the possibility of increasing the number of genes and maintaining the integrity of the original genome and its functions.

In the opinion of several authors (Grif 2007; Golubovsky 2000), there is one more type of mutation, which affects hereditary features and polymorphism of plant organisms. These are cytoplasmic mutations. This opinion is based on the data of possible independent (outside of chromosomes) existence of gene loci (blocks of genes) responsible for certain hereditary features in cytoplasm.

More in-depth modern studies of the biogenetic aspects of mutability and of evolution of woody plants and their adaptation to the environment involve newly developed methods and approaches to solving the problem at the genome level (Krutovsky 2006).

In the past decade, it has become possible to employ new types of molecular genetic markers with a known sequence of nucleotide buildup and known functions. Various molecular markers of expressed (i.e., capable of activation) genes were

obtained from those of dinucleotide nature to the full nucleotide sequence of genes – blocks of various genomes. Hundreds of thousands of such nucleotide sequences for many forest trees, including pine, spruce, poplar, and eucalyptus, have been discovered.

The full gene structure of the nuclear genome of the poplar *Populus trichocarpa* was determined in 2006 (Tuskan et al. 2006). The nuclear genome of this poplar with haploid number of chromosomes $n = 19$ has relatively small dimensions: about 500 Mb (1 Mb is the unit of measurement of genome length equal to one million nucleotides). The nuclear genome of the poplar has been found to hold more than 45,000 genes that code protein synthesis. However, a significant part of DNA molecule consists of “dormant” genes, which do not participate in protein synthesis. Scientists (Tuskan et al. 2006) believe that full DNA sequencing will help to identify the genes associated with biosynthesis of a lignocellulosic cell wall, with development of plant tissues, transport of metabolites, and with other important processes.

Biochemical reactions of synthesis of many compounds that proceed in a living woody organism involving various catalytic ferment systems are very complicated. Even a brief description of biosynthesis of basic wood components of interest to us would take up too much space and would be difficult for an unprepared reader to understand. We do not consider it advisable, because this subject goes beyond the issues addressed in this book.

2.3 Density and Moisture of Timber Species

Density is an essential characteristic of timber quality closely associated with its anatomy.

Structural features of timber directly affect not only its density but also capacity to interact with water molecules. And this in turn affects the thermophysical and mechanical properties of timber.

Timber density and moisture, as will be shown in later sections of the book, greatly affect the flammability and fire behavior of this material. It is known, however, that timber density and moisture are to some extent interrelated characteristics.

In the bone-dry state, the timber density, ρ_0 , may be taken as the ratio of dry sample mass, m_0 , to its volume, V_0 :

$$\rho_0 = m_0 / V_0, \text{ g/cm}^3 \left(\text{or kg/m}^3 \right)$$

Moistening bone-dry timber not only increases sample mass but also increases its volume due to swelling. It was noted that when timber is left in water or air with enhanced humidity, the sample volume increases only to a definite limit. This limit corresponds to full water saturation of the timber cell walls in the form of so-called imbibed water. A further increase in water content in timber due to the filling of

pores, capillaries, and other void spaces in the timber structure by so-called free water leads only to an increase in total sample mass without increasing moist timber volume.

As a result, moist timber density, expressed as the ratio of sample mass at a given moisture to its volume at the same moisture, increases significantly compared to the density of bone-dry timber.

In order to provide an accurate comparison of various timber species by density, the notions of density of timber with normalized moisture, as well as basic density (previously called conventional density), were introduced. Normalized timber density is the density of timber at 12 % moisture:

$$\rho_{12} = \frac{m_{12}}{V_{12}}$$

Basic density is expressed as the ratio of bone-dry sample mass to its volume at a moisture equal to or greater than the saturation limit of cell walls, V_{\max} :

$$\rho_b = \frac{m_0}{V_{\max}}$$

In effect, this parameter reflects the content of wood matter in the unit of volume of timber maximally swollen in water (including freshwood basic density estimation).

Along with the saturation limit of cell walls, W_{SL} , which is understood as the maximum moisture of cell walls when timber is moistened in water, the notion of wood hygroscopicity limit W_{HL} is also used. This parameter corresponds to the maximum moisture of cell walls achieved during sorption of water vapor from the air.

The hygroscopicity limit depends on the temperature, whereas the saturation limit of cell walls is not influenced by it. At zero temperature, these parameters nearly coincide: $W_{\text{SL}} = W_{\text{HL}}$, because at 0 °C W_{HL} reaches its maximum value. At temperatures above 0 °C, the condition $W_{\text{HL}} < W_{\text{SL}}$ is always observed for a specific timber variety.

Although the saturation limit of cell walls may vary from 22 to 53 % in different timber species depending on timber density, the figure often used in calculations is the average value $W_{\text{SL}} = 30$ % (Ugolev 2001). In the opinion of many authors (Chudinov 1984), the structure and chemical composition of timber (its species) also has an impact on its hygroscopicity limit. However, the hygroscopicity limit of various timber species at room temperature is recorded in a narrower range of values (from 22 to 35 %).

Average values of bone-dry timber density, basic density, and density of timber with normalized moisture for the most common timber species growing in Russia are given in Table 2.1 (Ugolev 2001; Poluboyarinov 1976).

Various timber species are subdivided by normalized density into low-density species ($\rho_{12} < 540 \text{ kg/m}^3$), medium-density ($550 < \rho_{12} < 740 \text{ kg/m}^3$), and high-density ($\rho_{12} > 750 \text{ kg/m}^3$). The lowest and highest densities are observed

Table 2.1 Average density values for various timber species

Species	ρ_0 , kg/m ³	ρ_{12} , kg/m ³	ρ_p , kg/m ³	Growing region
Dahurian larch	611	643	502	Far East
	583	613	472	Yakutia
Siberian larch	640	673	525	North, Urals
	621	653	509	Western Siberia
	603	634	494	Eastern Siberia
Common pine	476	505	405	Kola Peninsula
	495	525	421	Urals
	448	475	381	Western Siberia
	439	465	373	Eastern Siberia
Common fir	457	484	388	North European part
	429	455	365	Central part
Siberian fir	411	436	350	Eastern Siberia
	364	386	310	Western Siberia
	429	455	365	Far East
Cedar	402	426	342	Urals
	429	455	365	Altai
	420	445	357	Eastern Siberia
Siberian fir	383	406	326	Altai
	336	356	286	Western Siberia
	329	346	279	Eastern Siberia
Schmidt's birch	923	970	757	Primorye Territory
White birch	584	614	479	Central European part
Beech	607	643	516	Krasnodar Territory
White elm	513	544	436	European part
Hornbeam	753	792	618	Caucasus
Oak	679	720	577	Central European part
White willow	393	416	334	European part
Maple	650	690	570	European part
Lime	461	485	378	European part
Alder	427	452	363	Leningrad Region
Aspen	455	485	389	Central European part
Persian walnut	560	594	476	Caucasus
White poplar	393	413	334	European part
Black poplar	439	465	373	European part
Common ash	626	663	532	Central European part
Manchurian ash	616	653	524	Far East

in the foreign deciduous species balsa ($\rho_{12} = 120$ kg/m³) and lignum vitae ($\rho_{12} = 1,300$ kg/m³), respectively (Ugolev 2001). Among Russian species, as is seen from Table 2.1, Siberian Spruce from Eastern Siberia has very low density, whereas Schmidt's Birch from Primorye Territory has the highest density.

Density within the same species may vary depending on the ratio of earlywood and latewood layer dimensions in the growth layer, pith, and sapwood, which in turn depends on the conditions, soil, and climatic factors of tree growth (Shirnin et al. 2004).

The notion of specific gravity of timber is often used in the USA and other countries. This value, G_x , is considered as the relative density of timber, i.e., the ratio of timber density with specific moisture (x %) to water density at a temperature of 4 °C, where $\rho_w = 1.000 \text{ g/cm}^3$ (Glass and Felinka 2010). In this case, the value G_x is linked to the value ρ_x by the ratio:

$$G_x = \rho_x / \rho_w (1 + x/100) .$$

The question of the true density of wood matter usually identified with the material that forms the cell membranes is of special interest. It is assumed that true density of wood matter is equal for all species, because the components that form the cell walls do not differ much from each other in their density. Furthermore, cell membranes of woody plants of various species are nearly identical in structure and chemical composition.

The main difficulty in assessing the true density of wood matter:

$$\rho_{wm} = \frac{m_{wm}}{V_{wm}}$$

is in accurate determination of the volume occupied by wood matter in the test specimen. Experimental techniques based on measuring the volume of liquid or gas forced out by the wood specimen give various results depending on the capacity of the liquid or gas to penetrate the pores of the cell wall. The density of wood matter measured in water is the average value for all species amounting to 1.53 g/cm^3 , whereas when measured with helium and in nonpolar fluids (benzene, toluene, and mineral oil), it equals 1.46 and 1.44 g/cm^3 , respectively. The higher value of wood matter density obtained with water is believed (Ugolev 2001) to be due to apparent volume (V_{wm}) reduction due to penetration of molecules into cellulose microfibrils.

Based on data on the wood matter density in redwood and northern white cedar before and after withdrawal of extractive components (average values for these species are 1.505 and 1.530 g/cm^3 , respectively), the opinion was expressed that the chemical composition of wood affects ρ_{wm} value. The impact of extractive substances on wood matter density was also discovered in other species (Chudinov 1984). In earlier electron microscopy studies of cell wall density in different timber species, it was found that density values of cell walls were about 10 % lower compared to wood matter density. Despite rightful criticism of these results, the authors' conclusion that cell membrane density depends on timber variety and species and plant age, and may even change within the growth layer, is important (Chudinov 1984).

The assertion that the chemical components in the cell walls of woody plants differ little in density does not seem altogether proper to us. In fact, even cellulose that forms the wood frame and has an amorphocrystalline structure also typically has amorphous macromolecule sections with different densities arranged in crystallites. The true density of crystallites of known polymorphic modifications of native

cellulose 1 α and 1 β is 1.55 and 1.59 g/cm³. Disordered cellulose macromolecules usually localized in the space between microfibrils have noticeably lower density (Aleshina et al. 2001). The true density of lignin is about 1.25–1.36 g/cm³ (Ugolev 2001; Siau 1984). Unfortunately, we have not found the data on the true density of hemicelluloses. However, if we take as the upper limit the density of crystal modifications of monosaccharides, mannite, xylose, glucose, arabinose (1.489; 1.53; 1.544; 1.585 g/cm³), or disaccharides, saccharose, maltose (1.588; 1.540 g/cm³) (Perelman 1955), we should then expect the hemicelluloses, as oligo-carbohydrates with less ordered amorphous structure, to have true density of about 1.32–1.41 g/cm³.

The ratio between the bone-dry timber and true density of wood matter in this sample makes it possible to estimate the value of timber porosity, P :

$$P = \{1 - (\rho_0 / \rho_{wm})\} 100, \%$$

Timber porosity ranges from 40 to 77 % depending on the species.

Features of the morphological structure of timber significantly affect permeability – the capacity to conduct liquids or gases under pressure.

Timber permeability is experimentally determined by the velocity of water or air (nitrogen) transfer through a specimen's unit of area (GOST 16483.34 – 77). Determining gas permeability requires less time compared to water permeability. Due to the close correlation between these properties, the gas permeability parameters are used to assess the capacity of timber to soak up solutions of antiseptics, fire retardants, and other substances.

In order to compare various types of timber, it is recommended (GOST 16483.34 – 77) to use the gas permeability coefficient:

$$K_G = v h / P, \text{ m}^2 / \text{s MPa}$$

where v is the gas permeability, m³/(m²s); h is the specimen height, m; and P is the gage pressure, MPa.

A study of gas permeability of coniferous timber species in Siberia showed that pine specimens had the highest values of K_G (up to 2.2×10^{-3} m²/s MPa). Cedar and larch have lower K_G . Spruce has the lowest factor. All species show higher gas permeability in sapwood compared to heartwood (Ugolev 2001).

Table 2.2 shows an example of air permeability coefficients in the radial and tangential directions in a sapwood specimen of Siberian larch (Greb and Dzyga 2004).

The conclusion is that the air permeability coefficient of larch sapwood in the tangential direction is on average 22.5 times higher compared to the radial direction. In contrast to the radial direction, there is an end-to-end capillary system in the tangential direction. It consists of vertical tracheids connected by means of open bordered pores.

Table 2.2 Impact of gage pressure on air permeability coefficient in sapwood of Siberian larch

Pressure, MPa	Air permeability coefficient K_G , $\times 10^{-6}$ m ² /s MPa	
	Tangential direction	Radial direction
0.2	19.64	0.75
0.4	49.78	2.11
0.6	78.21	4.36

2.4 Thermophysical Properties of Timber Species

Many parameters of flammability and fire behavior of timber, like other organic materials, depend to a great extent on its thermophysical properties. This is only natural, because heating of a material exposed to an external source depends on the response of the material to the energy applied to its surface and on the way heat is transferred to the underlying layers.

Experimental and theoretical studies of flammability and fire behavior usually refer to such thermophysical characteristics as specific heat, thermal conductivity, thermal diffusivity, and thermal inertia. The last two parameters are inclusive, taking material density into account.

Specific heat of any system is defined as the ratio of amount of heat imparted to the system in a process to its temperature change. The general definition may be valid for systems consisting both of one and several components or several phases. Specific heat is the amount of heat needed to heat a unit of material (substance) mass by 1°. It is usually expressed in kJ/kg · K or J/g · K.

According to the Debye theory of solids, specific heat of a solid body is determined by the vibration frequency of its structure elements and by thermal-motion energy of these elements. The vibration spectrum of macromolecules of wood matter components includes torsional and pendulum vibrations of atoms and atom groups, deformation, skeletal vibrations of separate bonds and sections of the macromolecule chain, valence vibrations of various chemical bonds, and, finally, cooperative vibrations induced by incipency of macromolecule segmental mobility and by structural phase transitions from one state to the other.

Dry timber is a typical two-phase system consisting of wood matter and air. Specific heat of timber at constant pressure, c_P , hardly depends at all on its density. Since the mass fraction of air in the material is insignificant, specific heat of dry timber is determined by specific heat of wood matter. On the average for all species at 0 °C, it is assumed to equal $c_{P0} = 1.55$ kJ/kg · deg. (Ugolev 2001). According to other sources, $c_{P0} = 1.20$ (Glass and Felinka 2010) and 1.36 kJ/kg · deg. (Spearpoint and Quintiere 2001).

In timber moistening, when air is replaced with water, specific heat of timber is increased. Below the saturation limit of cell walls, the specific heat of moist timber equals the sum of specific heat of dry timber, specific heat of connected

water, and the increment caused by the additional energy of the water – water bond, A_c . The increment, A_c , depends not only on the water content in timber but also on temperature. In the temperature range 7–147 °C, the value of A_c is determined by the equation (Glass and Felinka 2010):

$$A_c = M (b_1 + b_2 T + b_3 M),$$

where M is the connected water content, %; T is the temperature, K; and coefficients $b_1 = -0.06191$; $b_2 = 2.36 \times 10^{-4}$; $b_3 = -1.3 \times 10^{-4}$.

When saturation limit of the cell walls is achieved (30 % moisture) at zero temperature, specific heat of timber increases to 2.2 kJ/kg · deg., whereas at 100 % moistening, it increases to 3.0 kJ/kg · deg. (Ugolev 2001).

Naturally, a temperature increase enhances the specific heat of timber, because when timber is heated, vibration motions of various structure elements of macromolecules are unfrozen. Specific heat of dry timber changes with temperature by a linear law, reaching almost 2.0 kJ/kg · deg. at 100 °C. According to (Janssens 1991), the relationship between temperature and specific heat may be expressed in the following way:

$$c_{p0}(T) = c_{pr}(T/T_r),$$

where c_{pr} is the specific heat of dry timber at temperature $T_r = 293$ K.

The impact of both temperature and moisture on specific heat of timber has been studied in the temperature interval from –40 °C to the boiling point of water (Ugolev 2001). Timber ignition occurs at a fairly high temperature. This being the case, it was suggested to use the value of specific heat of timber adjusted for the thermal properties of water (Simms and Law 1967):

$$c_{pW} = c_{p0} + (\Delta W + L + 4.19 \Theta_0) 0.01 (M/\Theta_{ign}),$$

where c_{pW} and c_{p0} – specific heat of timber of moist and dry timber, respectively; ΔW – heat of timber wetting, equals 66.9 kJ/kg; L – latent heat of water vaporization, equals 2,175 kJ/kg; Θ_0 – temperature change from environmental temperature to 100 °C; $\Theta_{ign} = (T_{ign} - T_0)$ – temperature change from environmental value to timber ignition temperature; and M – moisture content in timber, %. Coefficient 4.19 – latent vaporization heat of water.

The authors of work (Spearpoint and Quintiere 2001), following ignition experiments, have assessed specific heat of timber specimens cut from the trunk in crosswise and longitudinal directions relative to fiber orientation (Table 2.3).

The influence of anisotropy on the obtained characteristics is worth noting. Thermophysical properties are better in the longitudinal direction compared to crosswise. This effect is caused by different conditions of heat transfer, when heat flow is applied perpendicular to the specimen surface or parallel to the wood fiber axis, and by the different response of a material to temperature change.

Table 2.3 Values of thermal conductivity and specific heat for various directions of heat flow

Timber	Heat flow direction	Density, ρ_w , kg/m ³	k_w , W/m · deg.	C_{pw} , J/kg · deg.
Redwood	Across fibers	354	0.19	3,200
	Along fibers	328	0.85	7,400
Douglas fir	Across fibers	502	0.23	2,200
	Along fibers	455	0.80	4,000
Champion oak	Across fibers	753	0.44	3,100
	Along fibers	678	0.86	3,200
Maple	Across fibers	741	0.35	2,500
	Along fibers	742	–	7,100

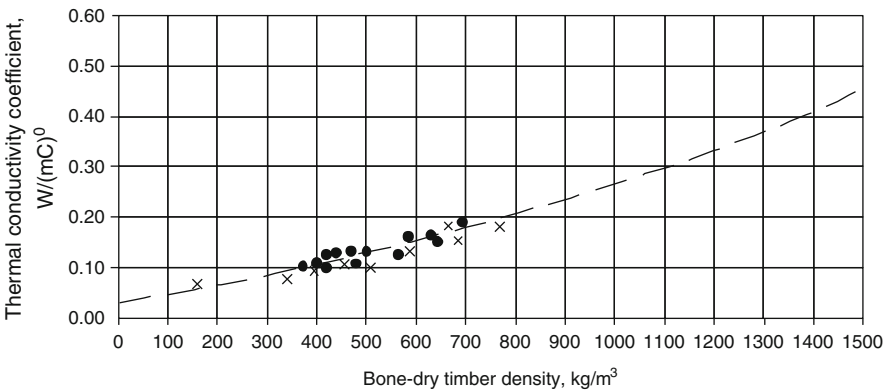


Fig. 2.6 Curve of thermal conductivity coefficient in crosswise direction to the fiber axis vs. timber density in bone-dry state

Thermal conductivity of timber in compliance with Fourier’s heat transfer law is described as the rate of heat flow through a unit of material surface area causing temperature drop, ΔT , on the heat flow path, l . Thermal conductivity, k , is numerically equal to the rate of heat flow in J/s through material with 1 m² surface area and 1 m thickness providing a temperature difference at the extremities of 1 K. Thermal conductivity of timber depends on various factors: timber density, temperature, water and extractive substance content, heat flow orientation in reference to fiber direction, and structural irregularities.

Figure 2.6 shows the influence of bone-dry timber density on the thermal conductivity coefficient in the crosswise direction to the fiber axis.

Extrapolation of the curve to the density assumed for the wood matter ($\rho_{wm} = 1,530$ kg/m³) gives a value of the wood matter thermal conductivity coefficient across the fibers of about 0.5 W/m · deg. (Ugolev 2001). Experimental data obtained by various scientists for the thermal conductivity coefficient of timber cell walls perpendicular to the fiber axis range from 0.40 to 0.44 W/m · K, whereas in the longitudinal direction, the range is $k_{||} = 0.67\text{--}0.88$ W/m · K. According to (Ugolev 2001), $k_{wm\perp} = 0.48$ for birch (in crosswise direction),

whereas $k_{\text{wmII}} = 0.948 \text{ W/m} \cdot \text{deg}$. The thermal conductivity coefficient of timber is much lower compared to that of wood matter (Fig. 2.6). At normal temperature and 12 % moisture, the values of k_{\perp} for many timber species range between 0.10 and 0.20 $\text{W/m} \cdot \text{deg}$.

Table 2.3 shows thermal conductivity coefficients of some specimens of coniferous and deciduous species for various fiber orientations in relation to the external heat flow. They were obtained from tests of timber ignition through exposure to radiative heat flow of 25–75 kW/m^2 (Spearpoint and Quintiere 2001). Thermal diffusivity and thermal inertia are physical parameters that characterize thermal inertial properties of material.

The thermal diffusivity is determined from the ratio:

$$a = k/\rho c, \text{ m}^2/\text{s}$$

and thermal inertia is the product of above parameters: $k\rho c$.

The thermal diffusivity of bone-dry timber decreases in proportion to material density enhancement, as is seen from the ratio above. It was demonstrated that with moisture below the saturation limit of cell walls, the thermal diffusivity of timber does not differ much from the same parameter for dry timber and ranges from 1.6– $2.1 \times 10^{-7} \text{ m}^2/\text{s}$ for various species (Ugolev 2001).

The effect of temperature should be more significant, because a temperature increase causes alteration of both thermal conductivity and specific heat of a material. However, to all appearances, due to the equivalent change of these values with a temperature increase up to 250–290 °C, thermal diffusivity, according to the data from various researchers, hardly depends at all on temperature within this range, yet is constant for every timber species (Spearpoint and Quintiere 2001).

In contrast to the thermal diffusivity, the thermal inertia parameter, $k\rho c$, depends heavily on temperature. This is precisely why the $k\rho c$ parameter derived from ignition tests is an effective value. It corresponds to the average material temperature between ignition and environmental temperatures. The value of the $k\rho c$ parameter obtained in this way is 1.6–2.6 times the value at 293 K (Ugolev 2001; Glass and Felinka 2010).

There is a very limited amount of published data pertaining to direct measurements of thermophysical properties of timber in a wide range of temperatures. Table 2.4 gives the values of thermal diffusivity and thermal inertia for some specimens of coniferous and deciduous species. The influence of external heat flow direction with respect to timber fiber axis is also shown.

High thermal inertia values obtained from ignition experiments with the heat flow applied to a timber specimen surface parallel to the fiber axis orientation are likely the result of enhanced temperature effect on the increase in specific heat and especially on the increase in the thermal conductivity coefficient under these heat transfer condition.

The observed general rule is enhanced thermal inertia of timber in proportion to the increase of its density. Moisture impact is also noticeable. Bone-dry timber from Moscow Region has the lowest $k\rho c$ value. Moisture content in other specimens from Table 2.4 was 4–8 %.

Table 2.4 Values of thermal diffusivity and thermal inertia for various timber species

Timber	Heat flow direction	ρ , kg/m ³	a , m ² /s	$k\rho c$, KJ ² /K ² m ⁴ s	References
Douglas fir	^a	465	–	0.158	Janssens (1991)
	⊥	502	1.79×10^{-7}	0.25	Spearpoint and Quintiere (2001)
	II	450	–	1.44	Spearpoint and Quintiere (2001)
Vietnam fir	⊥	400	–	0.148	Bui Din Than (2006)
Pine (Moscow Region)	⊥	450	1.84×10^{-7}	0.070	Sivenkov (2002)
Pine	⊥	460	–	0.156	Janssens (1991)
White pine	⊥	380	6.6×10^{-7}	–	Moghtadery et al. (1997)
Southern pine	⊥	508	–	0.183	Tran and White (1992)
Vietnam pine	⊥	430	–	0.173	Bui Din Than (2006)
Redwood	⊥	430	–	0.141	Janssens (1991)
	⊥	354	1.89×10^{-7}	0.22	Spearpoint and Quintiere (2001)
	II	328	–	2.07	Spearpoint and Quintiere (2001)
Thuja	^a	312	–	0.073	Tran and White (1992)
	⊥	330	–	0.087	Janssens (1991)
	^a	660	–	0.360	Tran and White (1992)
Red oak	⊥	753	1.74×10^{-7}	1.01	Spearpoint and Quintiere (2001)
	II	678	–	1.85	Spearpoint and Quintiere (2001)
	^a	530	1.0×10^{-7}	–	Moghtadery et al. (1997)
Maple	⊥	741	1.75×10^{-7}	0.67	Spearpoint and Quintiere (2001)
	II	742	–	1.09	Spearpoint and Quintiere (2001)
	^a	420	–	0.141	Tran and White (1992)
Lime	⊥	595	–	0.139	Bui Din Than (2006)
Vietnam eucalypt	^a	640	–	0.260	Janssens (1991)
Eucalypt	^a	810	–	0.393	Janssens (1991)
Vietnam acacia	⊥	560	–	0.140	Bui Din Than (2006)

^aHeat flow direction with respect to timber fiber orientation is not indicated. The data are likely to refer to an external heat flow perpendicular to the fiber axis

2.5 Effects of Heating on Mechanical Properties of Structural Timber and Timber Products

Mechanical properties of timber and its products are of great interest from the point of view of their practical use in building structures. Timber may be regarded as a viscoelastic anisotropic polymer composite. Its behavior under applied forces

and thermal effect is described by various parameters that specify the resulting strains and deformations. The major parameters are elastic modulus, E , and rigidity modulus, G (elastic modulus in shear), Poisson's ratio, and strength properties corresponding to deformations at the material breakdown limit. Since timber is anisotropic, each parameter may be represented by the values defined according to three directions of fibers in the material and to the growth layer: longitudinal, radial, and tangential.

Poisson's ratio expresses the ratio of material deformations in the crosswise and longitudinal directions to the applied load. The value of this ratio for various coniferous and deciduous species is intermediate between 0.5 and 0.9, typical for organic liquids, and 0.02–0.2, typical for reversible deformation of solids with amorphocrystalline structure. Elastic stress occurs in common solids (glass, quartz, metals, and polymers) as a result of the change in intermolecular distances of the material's chemical structure.

This consequently leads to increased volume of the deformed body and alteration of Poisson's ratio. The lower Poisson's ratio, the higher the material strength factor expressed as the ratio of compression strength to tensile strength. Poisson's ratios are affected by moisture content in timber.

At a temperature above the vitrifying point, the transition of solids into the high elastic state occurs. In this state, deformation is not accompanied by a change in volume. Elasticity has a diverse, entropic nature manifested in mobility of separate sections (linkages) of a material's chemical structure.

In everyday practice of timber material science, Poisson's ratio, μ , is not used, in spite of its clear physical content and relation to elasticity and rigidity moduli:

$$E = 2G (1 + \mu).$$

On the other hand, some of the frequently used parameters of mechanical properties of timber are considered important but purely technological characteristics. This is the case, for example, with timber static and shock hardness. These parameters are of interest because they may be assessed by nondestructive methods of material testing.

A lot of attention has recently been paid to the analysis and disclosure of the correlation between various mechanical properties of timber and the extent of their variability.

In work (Volynsky 2006), there is a report on statistical processing of the database of mechanical properties of 167 timber species with regard to their growing region in the former USSR. Coniferous and deciduous species have been analyzed as two separate statistical multitudes. In the same way, data on 112 species and their varieties – 47 coniferous and 65 deciduous – growing in the USA and Canada have been analyzed. In addition, certain data of mechanical properties of tropical timbers species have been included.

In fact, this database of mechanical properties covers the prevailing population of timber species growing on the Earth.

Tables 2.5, 2.6, 2.7, and 2.8 sum up the obtained results. It must be emphasized that each variation as such is an arithmetic average describing concrete species and

Table 2.5 Statistical values of mechanical properties of coniferous timber species in the USSR

Parameters	ρ_{basic} , kg/m ³	E_{bending} , GPa	H_{later} , N, mm ⁻²	σ_{compress} , MPa	σ_{bending} , MPa	σ_{tensile} , MPa	σ_{shear} , MPa
Average/min-max	485/346-725	11.1/7.42-16.8	22.2/14.1-38	46.8/33.6-69.5	80.6/43.8-117	93.7/50.5-131	7.57/4.05-12.2
Variant number	61	36	28	61	61	31	55
Coefficient of variation, %	18.0	21.4	28.7	16.7	18.7	24.4	21.0

Table 2.6 Statistical values of mechanical properties of deciduous timber species in the USSR

Parameters	ρ_{basic} , kg/m ³	E_{bending} , GPa	H_{laters} , N, mm ⁻²	σ_{compress} , MPa	σ_{bending} , MPa	σ_{tensile} , MPa	σ_{shear} , MPa
Average/min-max	647/337-973	10.59/4.38-16.7	47.2/15.7-110	52.6/31.4-81.7	97.0/55.7-160.0	113.2/63.2-212.0	10.3/4.67-19.0
Variant number	123	66	64	123	115	39	101
Coefficient of variation, %	20.0	24.7	41.0	18.7	22.7	29.0	30.9

Table 2.7 Statistical values of mechanical properties of coniferous timber species in the USA and Canada

Parameters	ρ_{basic} , kg/m ³	H_{later} , kN	E_{bending} , GPa	σ_{compress} , MPa	σ_{bending} , MPa	σ_{shear} , MPa
Average/ min–max	398/290–550	2.4/1.4–4.0	10.1/4.3–14.3	41.0/24.8–61.0	72/42–112	7.9/4.9–11.6
Variant number	68	43	68	68	68	66
Coefficient of variation, %	15.1	26.5	19.2	17.6	19.0	17.9

Table 2.8 Statistical values of mechanical properties of deciduous timber species in the USA and Canada

Parameters	ρ_{basic} , kg/m ³	E_{bending} , GPa	H_{later} , kN	σ_{bending} , MPa	σ_{compress} , MPa	σ_{shear} , MPa
Average/ min–max	568/340–880	11.1/7–15.7	4.7/1.6–8.1	91.4/47–139	46.1/27.7–70.2	11.6/5.4–18.3
Variant number	65	65	51	65	65	62
Coefficient of variation, %	20.1	19.7	35.3	25.8	21.0	25.2

Table 2.9 Statistical values of mechanical properties of tropical timber species

Parameters	ρ_{basic} , kg/m ³	E_{bending} , GPa	H_{later} , kN	σ_{bending} , MPa	σ_{compress} , MPa	σ_{shear} , MPa
Average/ min–max	533/170–920	12.4/3.8–25.5	5.1/0.4–16.3	96.0/19.3–181.4	50.8/11.7–92/5	10.7/2.1–17
Variant number	50	49	49	50	50	50
Coefficient of variation, %	29.0	31.1	65.7	33.5	31.2	29.7

growing region of the woody plant. For comparison, the tables show mechanical properties of clean timber species with normalized 12 % moisture and average values of basic density. It is easily determined; the impact of moisture above saturation limit on mechanical strength is insignificant; therefore, conversion into density at normalized moisture is possible. Strength parameters in the tables are given for longitudinal orientation of the load along the fibers. Values of static hardness refer to measurements on the lateral surface (in the radial direction relative to the fibers). Experience shows that there is a slight difference between static hardness values in radial and tangential directions. Timber static hardness on a lateral surface is 30–40 % lower compared to the crosscut end.

Variability of mechanical properties is defined by the coefficient of variation. As follows from the data above, timber density as well as compression and bending strength show the least variability. The greatest variability is observed in static specimen hardness.

Almost the same trend is typical for deciduous and coniferous timber species in the USA and Canada as well as for tropical species. In the latter case, greater variation in hardness may be noted (coefficient of variation 65.7 % – Table 2.9).

All datasets without exception follow Gauss's law. A clear-cut difference in timber density is especially evident between coniferous species from different hemispheres.

It is assumed that the higher density of domestic coniferous species compared to the USA and Canada plants is caused by harsher weather conditions in Russia, especially in Siberia.

Even at the level of two generalized statistical multitudes of timber, the important role of the density parameter may be noted in its impact on a material's mechanical properties.

The closest correlation between timber's mechanical properties and basic density is represented by power equations:

$$Y = aX^n.$$

The equations connecting strength (MPa) and basic density (kg m^{-3}) are given below.

For deciduous timber species of the USA and Canada:

$$\sigma_{\text{bending}} = 0.0598 \rho^{1.172}, \text{ correlation factor } R^2 = 0.807$$

$$\sigma_{\text{compres.}} = 0.1365 \rho^{0.932}, R^2 = 0.800$$

$$\sigma_{\text{shear}} = 0.006 \rho^{1.213}, R^2 = 0.832$$

For coniferous species:

$$\sigma_{\text{bending}} = 0.0716 \rho^{1.153}, R^2 = 0.790$$

$$\sigma_{\text{compres.}} = 0.0545 \rho^{1.105}, R^2 = 0.862$$

$$\sigma_{\text{shear}} = 0.03 \rho^{0.931}, R^2 = 0.587.$$

Equations of connection for domestic timber species are given separately, because they were established for smaller clean specimens and tested with slightly different standard procedures.

For deciduous timber species from various regions of the USSR:

$$\sigma_{\text{bending}} = 0.325 \rho^{0.879}, R^2 = 0.641$$

$$\sigma_{\text{compres.}} = 0.445 \rho^{0.737}, R^2 = 0.678$$

$$\sigma_{\text{shear}} = 0.0002 \rho^{1.022}, R^2 = 0.670$$

For coniferous species:

$$\sigma_{\text{bending}} = 0.271 \rho^{0.930}, R^2 = 0.701$$

$$\sigma_{\text{compres.}} = 0.309 \rho^{0.812}, R^2 = 0.762$$

$$\sigma_{\text{shear}} = 0.0131 \rho^{1.022}, R^2 = 0.665.$$

It is seen that "n" power in the obtained equations of connection is close to 1.

Therefore, in many studies, the dependence of timber's mechanical properties on density is assumed to be linear (Paul and Koukhta 2011).

A fairly close correlation between other mechanical parameters and density has also been revealed. Thus, an equation of connection was derived for lateral timber hardness (kN) at 12 % moisture and basic density:

$$\rho_{\text{basic}} = 267H^{0.438}, \text{ kg/m}^3$$

Analysis of the mechanical properties of small clean specimens of timber showed a strong relationship between strength parameters and elastic moduli. This permits to skip the measurements of all parameters and define only one or two of them. After that, by using the equation of connection, we may predict the other parameters with a margin of error not exceeding 7–8 %.

Thus, analysis of properties of coniferous species from the USA and Canada resulted in the following equation, which ties the bending strength with elastic module E_{bending} and lateral hardness H_{later} of the specimen (Volynsky 2006):

$$\sigma_{\text{bending}} = 6.035 + 4.428E_{\text{bending}} + 8.782H_{\text{later}}, R^2 = 0.891.$$

Bending strength is expressed here in MPa, elastic modulus in GPa, and hardness in kN. In this way, the following equation of relationship of parameters was derived for domestic coniferous timber species:

$$\sigma_{\text{bending}} = 31.8 + 3.16E_{\text{bending}} + 0.707H_{\text{later}}, R^2 = 817; \text{error} = 8.55 \, \%.$$

The following correlation between strength parameters has been found for small clean timber specimens:

$$\sigma_{\text{bending}} = \sigma_{\text{compres.}} (3\sigma_{\text{tensile}} - \sigma_{\text{compres.}}) / (\sigma_{\text{tensile}} + \sigma_{\text{compres.}}).$$

Hence, the axial tensile strength of a timber specimen may be estimated if bending strength and compression strength values are known.

The impact of scale effect on the mechanical properties of timber is worth noting. In larger sawn timber specimens, the strength parameters decrease substantially, some of them nearly twofold due to various flaws. Compression strength is least affected in imperfect large specimens.

Averaging the indices of mechanical properties over two large statistical multitudes of timber species results in an increase of coefficients of variation. But at the same time, it reveals the most crucial characteristics and shows their interrelation.

Variability of mechanical properties of concrete species of coniferous and deciduous timber can be inferred by the data given in Table 2.10 (Tkhan et al. 2006).

Comparison of mechanical properties of pine wood from various growing regions (subtropical climate of Vietnam and the European part of Russia) shows that they are very close and lie within the scatter in corresponding values. The timber of examined coniferous species has lower parameters of mechanical properties compared to those of deciduous species. Therefore, the high significance of the impact of timber density on its mechanical properties is confirmed.

Table 2.10 Mechanical properties of certain timber species

Parameter	Vietnam pine	Vietnam fir	Vietnam eucalypt	Acacia mangium	Vietnam acacia	Pine ^a (RF)	Oak ^a (RF)
ρ_{12} , kg/m ³ /min-max	460/410–510	420/370–510	620/570–670	540/470–610	580/480–680	470–520	640–870
σ_{bending} , MPa/min-max	69.3/54.83–83.9	62.17/43.05–81.3	109.45/88.45–130.0	109.66/86.1–133	118.22/85.3–151	67.4–86.2	114–163.6
E_{bending} , GPa	7.15	4.71	12.3	11.68	12.1	6.7–8	10–16.1
σ_{compress} , MPa/min-max	32.7/25.6–39.8	41.3/30.4–51.1	68.6/46.5–90.7	74.5/60.0–89	75.0/60.5–89.5	33–51	54–61
$\sigma_{\text{compress radial}}$, MPa/min-max	5.6/4.8–6.4	4.2/3.2–5.2	9.7/7.5–11.9	8.4/6.5–10.3	8.1/5.8–10.4	3.5	6.0
$\sigma_{\text{tensile along fibers}}$, MPa/min-max	78.0/67.0–89	37.2/25.0–49.4	140.7/121.4–160	140.1/121–159	112/92.1–132	78–115	120–144.6
$\sigma_{\text{shear along fibers}}$, MPa/min-max	10.45/9.25–11.6	8.24/7.2–9.2	16.56/15.4–17.7	11.8/8.1–15.5	9.38/7.8–10.9	6.0–7.7	7.8–13
$H_{\text{crosscut end}}$, MPa/min-max	37.46/32.1–75	43.71/30.4–84	78.81/75.2–82.4	74.83/72.2–85.4	65.52/56.0–75.0	24–32	63–107

^aGiven values are the average values of parameters for pine and oak trees growing in various regions of the RF and tested by procedure (GOST 16483; GSSSD 69–84)

It was found (Tkhan et al. 2006) that environmental moisture and temperature have considerable impact on the mechanical properties of timber. Moisture reduced the values of strength properties only within the range up to the saturation limit of cell walls. It mainly affected the strength of deciduous species. Thus, when moisture increases from 12 to 21 %, the bending strength of Vietnam pine decreased by 21 %, whereas that of eucalypt and acacia mangium decreased by 32.4 and 32.8 %, respectively. A similar trend was observed with moisture impact on static hardness of wood in crosscut view: in coniferous species, this parameter decreased 1.1–1.2 times, whereas in deciduous species it decreased almost 1.5 times.

Lower indices of mechanical properties are caused by plasticization effect of moisture, by reduced intermolecular interaction of wood components, and concentration of strains in places of structural heterogeneity of the material. The changes in the strength of moist specimen at constant room temperature we observed were reversible. After drying the specimen to initial moisture, the strength parameters regained their values (Tkhan et al. 2006).

The effect of moisture on mechanical properties of timber is addressed in a large number of scientific works. According to (Ugolev 2001), if timber moisture is reduced to 12 %, the tensile strength should increase according to the following equation:

$$\sigma_{\text{tensile}12} = \sigma_{\text{tensile}W} [1 + 0.01 (W - 12)].$$

According to the data of (Belyankin 1939), an average moisture increase of 1 % in various timber species results in a 3 % reduction in shear strength at room temperature.

As we see, moisture affects various parameters of mechanical properties of timber differently. The combined impact of moisture and elevated temperature appears to be even stronger. Thus, if compression strength of oak timber went down only three times with moistening at room temperature from 0 to 60 %, the combined increase in both moisture and temperature from 25 to 100 °C resulted in 15–20-fold strength reduction. On the other hand, the relative decrease in strength properties of bone-dry timber for a temperature increase to 40–100 °C was comparable with the impact of moisture alone (Belyankin 1939).

According to (Kollmann 1951), behavior of compression strength of bone-dry timber in the range from –160 to +160 °C is expressed in the equation:

$$\sigma_1 = \sigma_2 - k_T (T_2 - T_1) = \sigma_2 - 4.76\rho_0 (T_2 - T_1),$$

where ρ_0 is the density of bony-dry timber in g/cm³.

The majority of earlier works on the effect of elevated temperature on timber's mechanical properties were restricted to temperatures from subzero to 40–100 °C. They reported an investigation of timber in the process of its use or natural and forced drying.

In fire conditions, timber structures are more intensely heated. The temperature inside the material under the char layer formed in the process may vary from 250 to

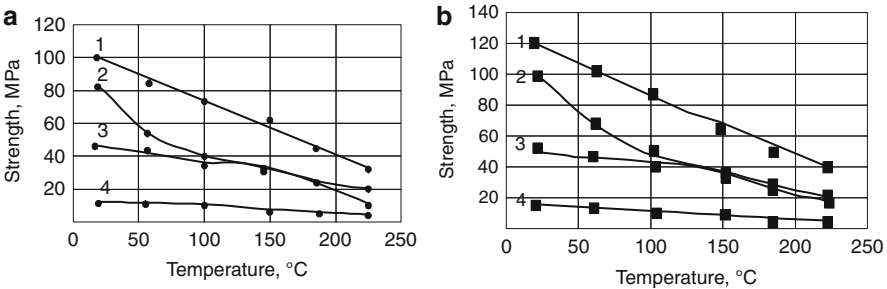


Fig. 2.7 Effect of elevated temperature on: 1 tensile, 2 bending, 3 compression, and 4 shear strength along fibers in pine (a) and larch (b) wood

Table 2.11 Values of temperature factor of reduction in mechanical properties for pine and larch timber within the range of 20–100 °C

Timber species	Factor k_T , MPa/degree (%/degree)			
	Tension	Compression	Shear	Bending
Pine	0.27 (0.30)	0.11 (0.25)	0.02 (0.22)	0.56 (0.68)
Larch	0.44 (0.36)	0.09 (0.17)	0.08 (0.36)	0.80 (0.72)

300 °C to normal affecting the bearing capacity of a structure. In the range above 240 °C, the physicochemical transformations in the timber structure accompanied by slight losses in mass significantly affect a material’s mechanical properties.

In this respect, works (Khmelidze et al. 1986; Rykov 1980), which report the results of determining timber’s mechanical properties at temperatures from 20 to 200–230 °C, are of interest.

Figure 2.7a, b show the effect of heating temperature on tensile, compression, shear, and bending strength of timber specimens along the fibers (Khmelidze et al. 1986).

These data were used (Volynsky 2006) to calculate the temperature factor k_T (above equation) up to 100 °C (Table 2.11).

On close examination of the figures, the bilinear character of the curves may be seen, the more evident in the case of bending strength. Up to 100 °C, a temperature change of 1 °C reduces timber bending strength by 0.68–0.72 %. Further on the slope of the curves decreased, due to evaporation of moisture from the specimen. Temperature impact on the changes in mechanical properties in various timber species may be illustrated in relative (%) rather than absolute units (Table 2.12). At temperatures of about 270–300 °C, timber strength is practically lost. Thus, experimental data in Table 2.12 are limited to temperatures of 230–250 °C.

As we see, exposure of various timber species to heat greatly impacts their mechanical properties. The domestic code (SP 64.13330.2011) recommends in design of timber structures excluding the crosscut sections of timber elements at temperatures exceeding 100 °C from consideration of load-bearing capacity.

Table 2.12 Relative change in mechanical properties of timber at elevated temperature

Species	Parameter, % change	50 °C	100 °C	150 °C	200 °C	230/250 °C	References
Pine	σ_{bending}	85/75	71/51	62/43	53/25	-/22	Khmelidze et al. (1986) and Rykov (1980)
Pine	E_{bending}	95	87	79	70	-	Nyman (1980)
Pine	$\sigma_{\text{compression}}$	76/89	58/70	46/51	34/32	-	Rykov (1980) and Nyman (1980)
Pine	σ_{tensile}	97/93	92/83	88/72	80/61	-	Rykov (1980) and Nyman (1980)
Pine	E_{tensile}	98	95	93	90	-	Nyman (1980)
Pine	σ_{shear}	95	85	50	21	4/0	Khmelidze et al. (1986)
Larch	σ_{bending}	74	41	38	26	21/-	Khmelidze et al. (1986)
Larch	$\sigma_{\text{compression}}$	90	81	79	54	34	Khmelidze et al. (1986)
Larch	σ_{tensile}	87	69	60	42	33	Khmelidze et al. (1986)
Larch	σ_{shear}	80	67	53	40	30	Khmelidze et al. (1986)
Fir	σ_{bending}	91	76	62	47	-	Nyman (1980)
Fir	E_{bending}	96	90	83	77	-	Nyman (1980)
Fir	$\sigma_{\text{compression}}$	91	77	63	49	-	Nyman (1980)
Fir	$E_{\text{compression}}$	98	94	90	87	-	Nyman (1980)
Fir	σ_{tensile}	95/	86	77	68	-	-
Fir	σ_{shear}	92	84	61	-	-	Bobacz (2008)
Fir	G_{shear}	79	71	36	-	0	Bobacz (2008)
Oak	σ_{bending}	83	67	50	29	16/-	-
Oak	$\sigma_{\text{compression}}$	81	63	57	48	28/-	-
Oak	σ_{tensile}	90	80	65	54	32/-	-
Oak	$\sigma_{\text{compr.across}}$	91	75	65	50	30/-	-

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